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Research Article

Quality of TEC Estimated with Mod_Ion Using GPS and GLONASS Data

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One of the largest sources of error in positioning and navigation with GNSS is the ionosphere, and the associated error is directly proportional to the TEC and inversely proportional to the square of the signal frequency that propagates through the ionosphere. The equatorial region, especially in Brazil, is where the highest spatial and temporal value variations of the TEC are seen, and where these various features of the ionosphere, such as the equatorial anomaly and scintillation, can be found. Thus, the development and assessments of ionospheric models are important. In this paper, the quality of the TEC was evaluated, as well as the systematic error in the L1 carrier and the inter-frequency biases of satellites and receivers estimated with the Mod_Ion, observable from GPS and integration with the GLONASS, collected with dual frequency receivers.

1. Introduction

The Global Navigation Satellite System (GNSS) is one of the most advanced technologies and has revolutionized the activities related to navigation and positioning from space technology. A main component of GNSS is the Global Positioning System (GPS), developed by the United States, and Global'naya Navigatsionnaya Sputnikowaya Sistema (GLONASS) of responsibility of the Republic of Russia. A relevant fact is that, in December 2005, the first GALILEO satellite was launched, which is being developed by the European Union and must come into operation in 2013. The GNSS is composed by the so-called (Satellite Based Augmentation System) SBAS, such as the Wide Area Augmentation System (WAAS) in USA, European Geostationary Navigation Overlay Service (EGNOS) in Europe, Multi-functional Satellite-Based Augmentation Service (MSAS) in Japan, and Satellite Navigation Augmentation System (SNAS) in China [1].

In general, most users simply use the GNSS system to get their coordinates, without being committed to details, but for the quality of information (precision) provided by it, except aviation. This quality information is very optimistic, demanding attention from users. However, certain applications require the knowledge of the various processes related to the system. The mitigation of the effects of the atmosphere (troposphere and ionosphere) over GNSS observables requires knowledge of the signal analysis and its behavior in the atmosphere, requiring interaction with other sciences such as Aeronomy, Meteorology, among others. Accordingly, this interaction allows studies related to the behavior of the ionosphere and the troposphere to be made from GNSS observables. In Brazil, the ionosphere shows a very complex behavior, for being located near the geomagnetic equator, requiring the development of models and appropriate studies for the region [1–12].

With the Selective Availability (SA) deactivation, in the case of GPS, the error due to the ionosphere has become a major source of systematic error in positioning, especially in periods of high solar activity for one frequency GNSS users, in the conventional point positioning as well as relative positioning. Another effect that affects considerably the GNSS signals is ionosphere scintillation, a result of propagating the signal through a region in which there are irregularities in the density of electrons.

The error due to the ionosphere depends on the Total Electron Content (TEC) present in the ionosphere and in signal frequency. Users of, at least, dual frequency receivers can make corrections of this effect, using the ionospheric free linear combination. This observable eliminates first-order ionospheric effect. Users of single frequency receivers, however, need to correct the systematic effect observables due to the ionosphere. The quantification of this effect can be done by [3, 4, 12]: coefficients transmitted by navigation messages, using the Klobuchar model; observations collected with one or dual frequency GNSS receivers of (Ionosphere map Exchange format) IONEX archives obtained from Global Ionospheric Maps (GIM), which provide values of vertical TEC (VTEC) in a grid with spatial resolution of $5^{\circ} \times 2.5^{\circ}$ in longitude and latitude, respectively, and temporal resolution of 2 hours [13].

In the geodetic community, one of the models used and implemented in commercial software, to minimize the effects of the ionosphere on GPS observables, is the Klobuchar model. This model, also called Broadcast model, estimates the systematic error due to the ionosphere to one frequency receivers [14] and its coefficients are transmitted by GPS satellites in navigation messages. However, this model removes around 50% to 60% of the total effect [15, 16]. Being more appropriate for use in regions of middle latitudes, which is the more predictable ionospheric region, where the ionosphere has a more regular behavior. However, this is not an appropriate model to be used in Brazil, where there is high variation in the density of electrons as well as in South America. So with the need to have a more effective correction strategy of the ionosphere effect, several models were developed by various research centers and universities, using observations collected with dual frequency GPS receivers. In terms of South America, we can quote the (La Plata Ionospheric Model) LPIM model, developed at (Astronomical and Geophysical Sciences Faculty of Universidad Nacional de La Plata) FCAG/UNLP, Argentine [2] and the Regional Model of Ionosphere (Mod_Ion) developed in FCT/UNESP, Brazil [3].

The accuracy of VTEC values in the final IONEX files grid (~11 days of latency) is 2–8 TEC units (TECUs) and for rapid files (<24 hours) of 2–9 TECU [17]. Ciraolo et al. [18], in a calibration process, determined the interfrequency bias (IFB) of a pair of receivers, which ranged from 1.4 to 8.8 TECU. This paper aims to assess the quality of TEC and the error in the L_1 carrier estimated with the Mod_Ion, from GPS observables and integration with the ones from GLONASS, collected with dual frequency receivers.

The paper is organized as follows. In Section 2 there is a brief description of impact of the ionosphere on the propagation of GNSS signals; Section 3 describes the equations, based on the geometry-free linear combination of observables collected with dual frequency receivers, used in the Mod_Ion, as well as gets the TEC and the systematic error due to the ionosphere in the L_1 carrier, and some aspects of adjustment by the least squares; the results and analysis of the experiments in order to verify the quality of the TEC provided by model, as well as the IFB of the satellites and receivers are presented in Section 4; based on the experiments, conclusions and future works will be presented in Section 5.

2. Impact of the Ionosphere on the Propagation of GNSS Signals

The terrestrial atmosphere, for practical purposes, can be considered as a set of gas layers, spherical and concentric to the Earth. Its structure is related to various thermal, chemical, and electromagnetic elements. These combined parameters vary depending on the time, latitude, longitude, time of year, and solar activity.

With respect to the propagation of electromagnetic waves, the Earth's atmosphere is divided into ionosphere and troposphere. In this division, the troposphere is the layer between the Earth's surface up to 50 km in height. It is composed of neutral particles, and the highest concentration of gas is found on up to a height of 12 km, consisting of nitrogen, oxygen, carbon dioxide, argon, water vapor, among others. The propagation of the signal in the troposphere depends mainly on the water vapor content, air pressures, and temperature. For frequencies below 30 GHz, the refraction does not depend on the frequency of the signal transmitted [16].

The ionosphere is defined as the portion of the upper atmosphere, where there is sufficient ionization to affect the propagation of radio waves [19]. Unlike the troposphere, it is a dispersive medium; that is, in this case, signal propagation depends on the frequency. It is characterized mainly by the formation of ions and electrons, and it starts at around 50 km, extending to approximately 1000 km in height.

In the region covered by the ionosphere, the electron density is sufficient to alter the propagation of electromagnetic waves. The ions and free electrons in the ionosphere are mainly created by the process of photo ionization. The ionospheric photo ionization is the absorption of solar radiation, predominantly in the range of extreme ultraviolet and X-rays by neutral atmospheric elements [19–21]. The ionosphere as a dispersive means affects the modulation and phase of the carrier, causing, respectively, a delay and an advance [16]. The delay is also referred to as ionospheric delay and increases the apparent length of the path traveled by the signal.

The troposphere effects on GNSS signals are usually reduced by processing techniques or determined directly by models. Since it is not possible to assess the atmospheric pressure and temperature along the route of the signal through the neutral layer, there are several models available, which correct for 92% to 95% of this effect [22]. In contrast, the ionosphere effect, which depends on frequency and, hence, on the refractive index proportional to the TEC, that is, to the number of electrons present along the path between the satellite and the receiver. If the TEC values were constant, the effects caused by the ionosphere would be easy to determine. The problem is that the TEC varies in time and space, in relation daytime, season, solar cycle, geographical location of the receiver and Earth's magnetic field, and so forth. Besides the refraction effect, these variations can cause the receiver to go out of tune with the satellite, by weakening the signal strength, the specific case of the phenomenon known as scintillation.

Table 1: Maximum vertical ionospheric range error (m).

Frequency	1st-order effect ($1/f^2$)	2nd-order effect ($1/f^3$)	3rd-order effect ($1/f^4$)
L_1	32.5	0.036	0.002
L_2	53.5	0.076	0.007
L_0	0.0	0.026	0.006

The ionosphere effects are divided into effects of 1st, 2nd, and 3rd order. Table 1 shows the maximum error in the vertical direction, which can be expected for the GPS L_1, L_2 carriers and for the ionospheric free linear combination (L_0). For inclined directions, the influence increases [1].

The error or effect of 1st order, due to the ionosphere in phase (I_{fr}^s) and pseudorange (I_{gr}^s) along the satellite direction (s) and receiver antenna (r), is given according to the TEC and the frequency of the signal (f) [3, 16]:

$$I_{fr}^s = -\frac{40.3}{f^2}\text{TEC}, \tag{2.1}$$

$$I_{gr}^s = \frac{40.3}{f^2}\text{TEC}. \tag{2.2}$$

According to (2.1) and (2.2), we can see that the errors due to the ionosphere for the phase and pseudorange have the same magnitude but opposite signs. Both are proportional to the TEC and inversely proportional to the square of the frequency of the carrier. The TEC unit (TECU) is given in electrons per square meter (el/m^2) and the constant $40.3\,\text{m}\,\text{Hz}^2(\text{el}/\text{m}^2)^{-1}$. The effect of first order can be obtained from the free geometry linear combination using observables collected with GPS receivers and/or dual frequency GPS/GLONASS, and the remaining error represents a few centimeters [1].

The effect of second order of the ionosphere depends on, besides the TEC and the frequency, geomagnetic induction at the point where the signal passes through the layer of the ionosphere and the angle of the signal in the geomagnetic induction vector. Unlike the effect of first order which is the same and has opposite signals to the phase and pseudorange, the one of the second order of the phase is half of the second-order effect of the group [23].

But the effect of third order does not depend on the magnetic field, but is a function of maximum density of electrons, at the phase the effect is equivalent to one third of the pseudorange effect [23].

2.1. Regular Variations of the TEC

The regular temporal changes of the TEC include daytime and seasonal variations and cycles of long periods. The daytime variation is mainly due to Sunlight, that is, solar radiation. Throughout the day, the density of electrons depends on the local time, with its peak occurring between 12 and 16 local times [24]. In the low latitude equatorial region, a second peak occurs in the hours preceding midnight, especially in periods close to the equinoxes and to the summer and during periods of high solar activity.

Seasons also influence variation in electron density, due to the change in the zenithal angle of the sun and the intensity of the ionization flow, characterizing seasonal variations. During the equinoxes, the effects of the ionosphere are bigger, whereas in the solstices, they are smaller [5].

Changes in long-period cycles, with cycles of approximately 11 years, are associated with the occurrence of sunspots and the increase of ionization and thus the TEC is proportional to the number of spots.

The geographic location also influences the variation of the density of electrons in the ionosphere, because the overall structure of the ionosphere is not homogeneous. It changes with latitude, due to the variation of the zenithal angle of the Sun, which influences directly, the level of radiation, which changes, in turn, the density of electrons in the ionosphere. The equatorial regions are characterized by a high density of electrons and have a high spatial variation. The regions of middle latitudes, however, are considered relatively free from ionospheric abnormalities, presenting a more regular behavior, close to that described by theoretical models. The ionosphere over the north and south poles, alternatively, known as polar or high latitudes ionosphere, is extremely unstable [20]. More details on the changes of regular TEC can be obtained, for example, from [19, 20].

3. Regional Ionosphere Model (Mod_Ion)

The Mod_Ion was developed in FCT/UNESP to represent the ionosphere in an analytical way [3]. The parameters of the model are estimated from data collected with dual frequency GNSS receivers. With the introduction of several receivers it was possible to also estimate the systematic error due to satellites and receivers, called Differential Code Bias (DCB) or IFB, caused by the signal route on the hardware of satellites, until it was spread out on space, and on antenna cables and hardware of receivers, until the signal decorrelation.

The adjustment by the Least Squares Method (LSM) with constraints is used in bath in the process of estimating the parameters of the model. The GNSS observable used in the calculation of the TEC or the systematic error due to the ionosphere in the L_1 carrier is the pseudorange filtered by the carrier phase [25]. The original observable can also be used as well as the carrier phase.

3.1. Ionospheric Model

Models that use GNSS data are based on the geometry-free linear combination of observables collected with dual frequency receivers. In the derivation of the model, errors due to nonsynchronism of the satellite and receiver, ephemeredes and the tropospheric refraction are neglected, since their effects contaminate both frequencies the same way and do not affect the validity of results.

The model is based on the difference between the pseudoranges of the carriers L_2 and L_1, with frequencies f_2 and f_1 of signals generated by the satellites that are part of the GNSS [3]:

$$P_{2r}^{s} - P_{1r}^{s} = I_{2r}^{s} - I_{1r}^{s} + \left(S_{p2}^{s} - S_{p1}^{s}\right) + \left(R_{p2} - R_{p1}\right) + \varepsilon_{p21}. \tag{3.1}$$

From (2.2) we have

$$I_{2r}^{s} - I_{1r}^{s} = 40.3\,\mathrm{TEC}^{s}\frac{f_1^2 - f_2^2}{f_1^2 f_2^2} = I_{1r}^{s}\frac{f_1^2 - f_2^2}{f_2^2}, \tag{3.2}$$

thus

$$F^{\mathrm{TEC}}\left(P_{2r}^{s} - P_{1r}^{s}\right) = \mathrm{TEC}_r^s + F^{\mathrm{TEC}}\left[\left(S_{p2}^{s} - S_{p1}^{s}\right) + \left(R_{p2} - R_{p1}\right)\right] + F^{\mathrm{TEC}}\varepsilon_{p21} \tag{3.3}$$

or

$$F^{I_1}\left(P_{2r}^{s} - P_{1r}^{s}\right) = I_{1r}^{s} + F^{I_1}\left[\left(S_{p2}^{s} - S_{p1}^{s}\right) + \left(R_{p2} - R_{p1}\right)\right] + F^{I_1}\varepsilon_{p21}. \tag{3.4}$$

Equation (3.3) is the observation equation of Mod_Ion used to calculate the TEC in the satellite/receiver direction. The unknowns $(S_{p2}^{s} - S_{p1}^{s})$ and $(R_{p2} - R_{p1})$ represent, respectively, the IFBs of satellites and receivers, and ε_{P21} represents another differential remaining errors (multipath, receiver noise, etc.), where $F^{\mathrm{TEC}} = f_1^2 f_2^2/40.3(f_1^2 - f_2^2)$, in general representing a constant for the GPS satellites and particularly for each of the GLONASS satellites.

By (3.4), one can calculate the ionospheric delay, that is, ionospheric error (I_{1r}^{s}) in the L_1 carrier, in the satellite/receiver direction, with $F^{I_1} = f_2^2/(f_1^2 - f_2^2)$.

The TEC or the ionospheric delay along the path of the satellite/receiver can be obtained according to the VTEC or the vertical ionospheric delay (I_1^v), by the expression, assigned as standard geometric mapping function $(1/\cos z')$, which provides the slant factor, like this

$$\mathrm{TEC}_r^s = \frac{\mathrm{VTEC}}{\cos z_r'^s} \tag{3.5}$$

or

$$I_{1r}^{s} = \frac{I_1^v}{\cos z_r''^s} \tag{3.6}$$

for a receiver (r), z'^s is the zenithal angle of the signal path from the satellite (s) to a ionospheric point located in a ionospheric layer, for example, of 400 km of height. Then

$$F^{\mathrm{TEC}}\left(P_{2r}^{s} - P_{1r}^{s}\right) = \frac{\mathrm{VTEC}}{\cos z_r'^s} + F^{\mathrm{TEC}}\left[\left(S_{p2}^{s} - S_{p1}^{s}\right) + \left(R_{p2} - R_{p1}\right)\right] + F^{\mathrm{TEC}}\varepsilon_{p21} \tag{3.7}$$

or

$$F^{I_1}\left(P_{2r}^{s} - P_{1r}^{s}\right) = \frac{I_1^v}{\cos z_r'^s} + F^{I_1}\left[\left(S_{p2}^{s} - S_{p1}^{s}\right) + \left(R_{p2} - R_{p1}\right)\right] + F^{I_1}\varepsilon_{p21}. \tag{3.8}$$

Due to the periodic nature of the effect, to model the diurnal behavior of the VTEC or the error in the L_1 carrier [10] use the series

$$\begin{aligned} \text{VTEC or } I_1^V = a_1 + a_2 B^s + \sum_{\substack{i=1 \\ j=2i+1}}^{n=4} \left\{ a_j \cos(iB^s) + a_{j+1} \sin(iB^s) \right\} \\ + a_{n^*2+3} h^2 + \sum_{\substack{i=1 \\ j=2i+10}}^{m=4} \left\{ a_j \cos(ih^s) + a_{j+1} \sin(ih^s) \right\}. \end{aligned} \tag{3.9}$$

The variable B^s represents geographic latitude of the subionospheric point (projection of a point on ionospheric layer on the earth surface) and variable h^s is given as

$$h^s = \frac{2\pi}{T}\left(t - 14^h\right), \tag{3.10}$$

where T represents the 24-hour period and t the local time of the subionospheric point.

The total number of parameters of the model is given by $4^*4 + 3 + r + s$, where the 4^*4+3 represent the coefficients of the series, **r** is the receivers IFB, a total equal to the number of receivers used in the network, and **s** is the satellites IFB, which is equal to the number of satellites tracked to determine the parameters of the model.

In adjustment by least squares, matrix A shows rank deficiency, equal to two. This implies that satellite or receivers IFBs have to be determined for two of them, one regarding GPS and the other regarding GLONASS. Thus, the constraints were imposed in one of the GPS/GLONASS receivers.

4. Experiments, Results, and Analysis

The experiments were performed at the Laboratory of Space Geodesy of the FCT/UNESP, where 4 dual frequency GPS/GLONASS receivers were connected to a TRM 55971.00 Zephyr GNSS Geodetic Model 2 Antenna, using a splitter with 4 outputs. Data were collected for 15 days in the year 2007 (132 to 137, 153 to 157, and 173 to 177) using 2 Topcon TPS HYPER GGD (H826 and H819), TRIMBLE NTR5, and LEICA GRX1200 GGPRO receivers. Two experiments were conducted, the first using only GPS observables, and the second aiming the integration of GPS and GLONASS systems. The experiments were conducted using data in RINEX format, with observables collected every 15 seconds, with 20 degrees elevation. The precise ephemerides and satellite clocks of the International GNNS Service (IGS) were used. It is worth mentioning that all experiments passed the quality control of adjustment and, according to the Dst geomagnetic index, the observables were collected in condition of weak geomagnetic storm (−30 nT to −50 nT), and that on days in question they did not exceed −25 nT.

Receiver H826 was chosen as a reference for estimation of IFBs, and relatively constrained as zero and weight tending to infinity, since the value of the receivers IFB is unknown. Some GLONASS satellites did not participate in some days, for being under maintenance in the quoted period (http://gge.unb.ca/Resources/GLONASSConstellationPlot.pdf).

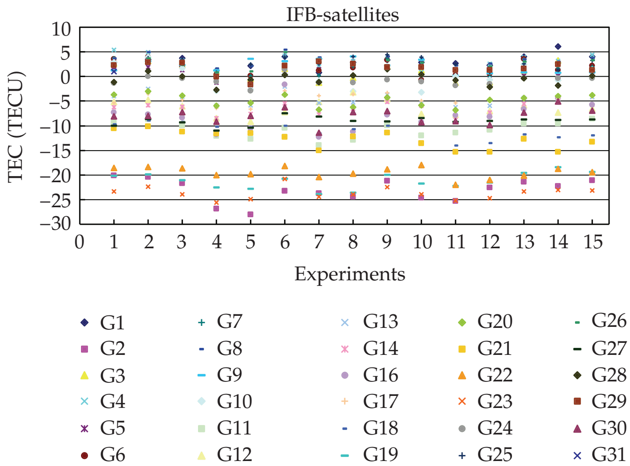


Figure 1: GPS satellite IFB—Error in TEC.

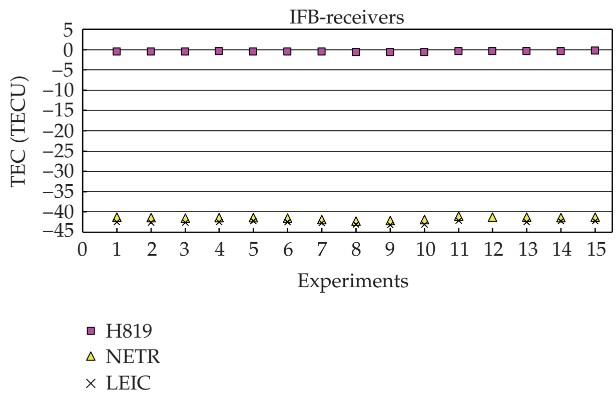


Figure 2: GPS receiver IFB—Error in TEC.

It was yet adopted as a criterion for rejection of the observables, the standard one, which represents the upper limit of change in the TEC for static users, given by 0.1×10^{16} (el/m^2) per second [26]. This value represents 0.085 Hz in L_1 (GPS) and corresponds to 0.0163 m/s of change in pseudoranges due to the ionospheric effect. The differences between consecutive linear combinations bigger than 0.0163 m/s imply the rejection of the observables used to estimate the parameters of the model.

4.1. Satellites and Receivers IFBs Obtained with GPS Observables

Using established procedures, the satellite and receiver IFBs were estimated, as well as the coefficients of the series that allows the calculation of the VTEC considering only the GPS observables. On Figures 1 and 2, the satellites and receivers IFBs are presented, in TECU. Experiments 1 to 5 correspond to the days of the year 133 to 137 of 2007, 6 to 10 correspond to days 153 to 157/2007, and 11 to 15 correspond to days 173 to 177/2007.

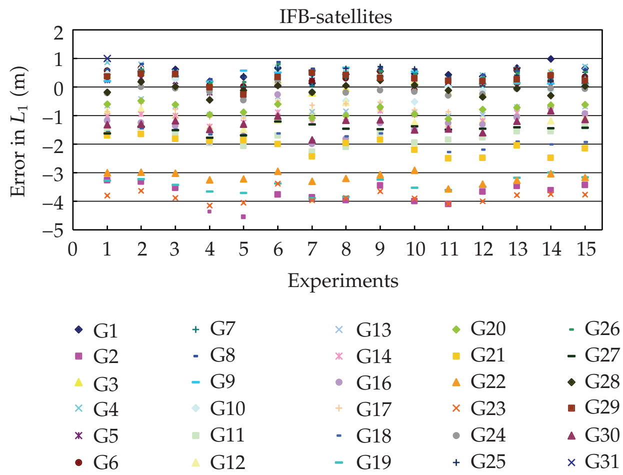


Figure 3: GPS satellite IFB—Error in L_1.

Analyzing Figure 1, we find that the satellites IFBs showed a similar behavior, except for satellite 2 (G2) in the 4th and 5th experiments, and satellite 16 (G16), whose variation was 10.658 TECU. This behavior shows that the systematic errors of the satellites are not stable. It is worth mentioning that the IFBs of satellites include the IFB of receiver H826 which was adopted as reference. The Root Mean Square (RMS) error indicates that you can estimate the IFBs of satellites with precision, better than 2.735 TECU.

The receiver IFB of H826 was constrained as being zero, the values receivers IFBs were estimated in relation to the receiver. On Figure 2, we observed that receivers showed a behavior very similar and stable, but with different values for each. Receiver H819 features an IFB very close to the one adopted as reference, with an average of −0.500 TECU. For receivers NETR and LEIC, the values were, for the trial period, respectively, −41.510 and −42.564 TECU. The variation of the IFB of receivers was around 9 times less than the ones of satellites, indicating the stability of the receivers. The RMS indicates that one can estimate the IFBs of receivers with accuracy better than 0.329 TECU.

Regarding IFBs in L_1 carrier, which represent the systematic error that affects GPS observables made in L_1, values can be obtained using (2.2) or through the Mod_Ion. To determine the error in GPS L_2 carrier can also be used by the same equation or multiply the error in L_1 by the constant 1.64694. Figures 3 and 4 show IFBs due to satellites and receivers for L_1 carrier, in units of m, respectively.

The error in the L_1 carrier due to satellites showed RMS better than 0.444 m and the receivers better than 0.054 m.

4.2. VTEC Obtained with GPS Observables

From geometry-free linear combination (see (3.3)), applying the correction of IFBs due to satellites and receivers can get a set of values of VTEC for each of the 4 receivers. To calculate the differences of VTEC, they took as reference the value obtained from the 19 coefficients estimated for the series (see (3.9)), which analytically represents the ionosphere. Figures 5 to 7 show the discrepancies of VTEC in the quoted period. For each of the experiments it is also presented the values of VTEC determined analytically, and used as reference.

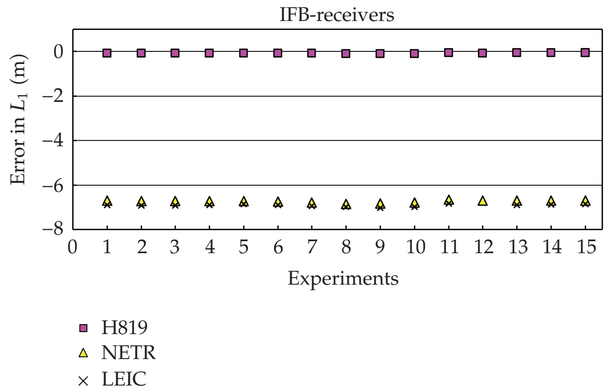


Figure 4: GPS receiver IFB—Error in L_1.

Analyzing Figures 5, 6, and 7, we see that the values of VTEC did not exceed 30 units, because the experiments were conducted over a period of low solar activity. The receivers of the same manufacturer (H826 and H819) have the same behavior for the discrepancies of VTEC, and the daily average is less than −0.227 VTEC units, the RMS indicates that the precision with which the VTEC is estimated is better than 2.365 units, and the biggest discrepancy was −10.917 units. The behavior of receiver NTER is noisier and the daily average and RMS of discrepancies are better than, respectively, −0.244 and 2.396 VTEC units. Regarding receiver LEIC, there is a little higher value than the other, with daily average of discrepancies of up to −0.337 units and RMS of 2.713 VTEC units. The modeling also shows a systematic error, as all the daily average of discrepancies show the same bias, that is, the same signal.

4.3. Satellites and Receivers IFBs Obtained with GPS/GLONASS Observables

In this experiment for the weight of GLONASS observables was assigned a scale factor of 1/2 on the GPS, because fundamental frequency is half the frequency of the GPS. The experiment was conducted only with data collected between the days of the year from 133 to 137 of 2007, and receiver LEIC did not participate because it did not collect GLONASS observables in this period. In Figure 8, it is presented the IFBs due to GPS and GLONASS satellites and, in Figure 9, the ones due to receivers.

On Figure 8, we find that the GPS satellites IFBs had a very similar behavior, contrary to what occurred with the most part of GLONASS satellites. For GPS satellites, in relation to IFBs determined only with GPS observables, the biggest difference to the RMS was 1.675 TECU (G14). The GLONASS satellites showed the biggest variation in the determination of IFBs, reaching 36.191 TECU, with the RMS value of 12.727 TECU (R14).

GPS receiver IFBs (Figure 9) are much more stable than those of the GLONASS receivers. In the previous experiment, the biggest difference of the averages for the GPS did not exceed 0.567 TECU, with RMS of 0.164 TECU. The IBFs related to GLONASS observables have much variation in the order of up to 13.167 TECU, with values very dispersed in relation to the average, with RMS being 3.994 and 4.364 TECU, respectively, for H819 and NETR.

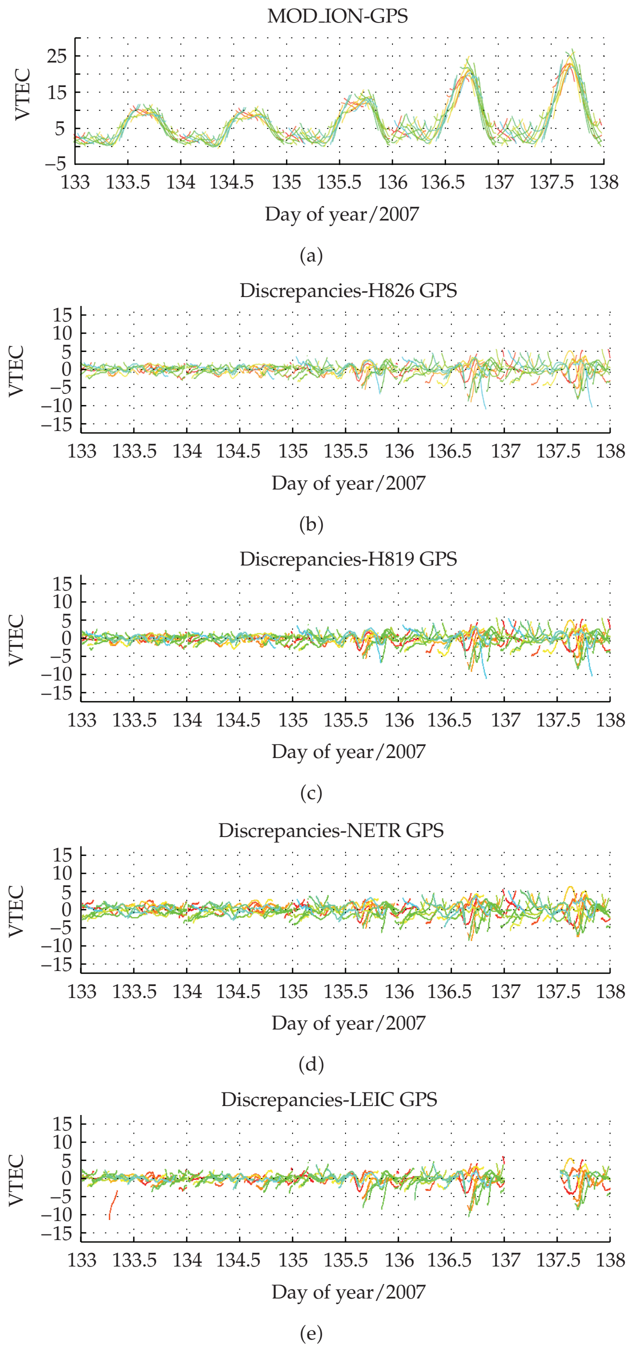
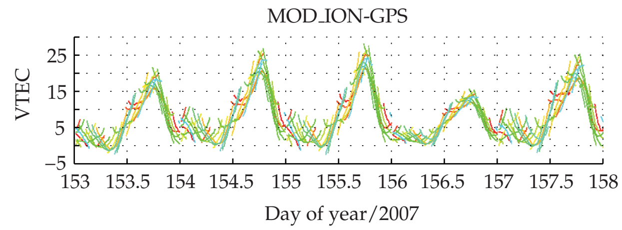


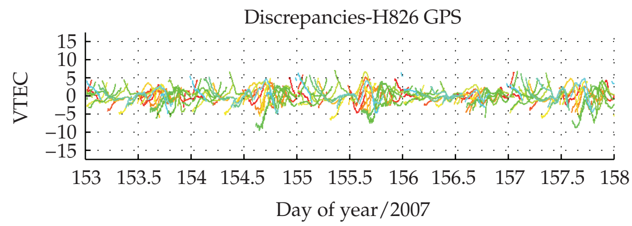
Figure 5: VTEC and discrepancies (GPS: 133 to 137/2007).

4.4. VTEC Obtained with GPS/GLONASS Observables

To evaluate the quality of the TEC obtained with Mod_Ion, a modeling was conducted using the GPS and GLONASS observables simultaneously. Figure 10 shows the daily difference in the quoted period, including the modeled VTEC.



(a)



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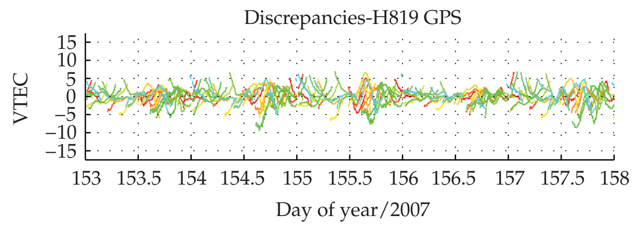

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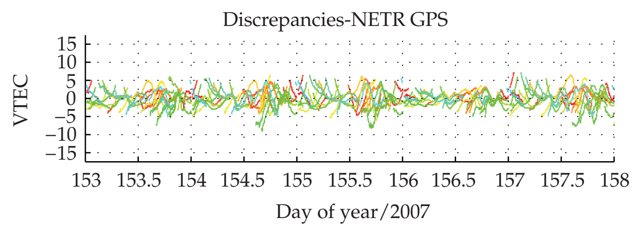

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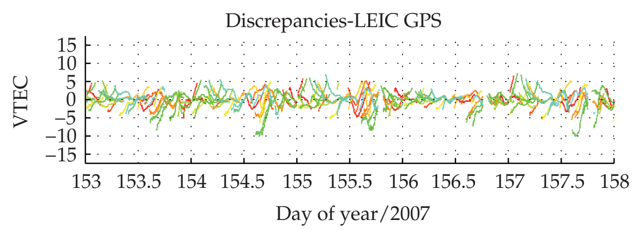

(e)

Figure 6: VTEC and discrepancies (GPS: 153 to 157/2007).

The behavior of the VTEC discrepancies (Figure 10) regarding receivers H826, H819, and NETR are similar, the daily average is less than −0.891 VTEC units and RMS is better than 4.929 VTEC. The biggest discrepancy was −30.409 VTEC units, related to the influences of GLONASS satellites.

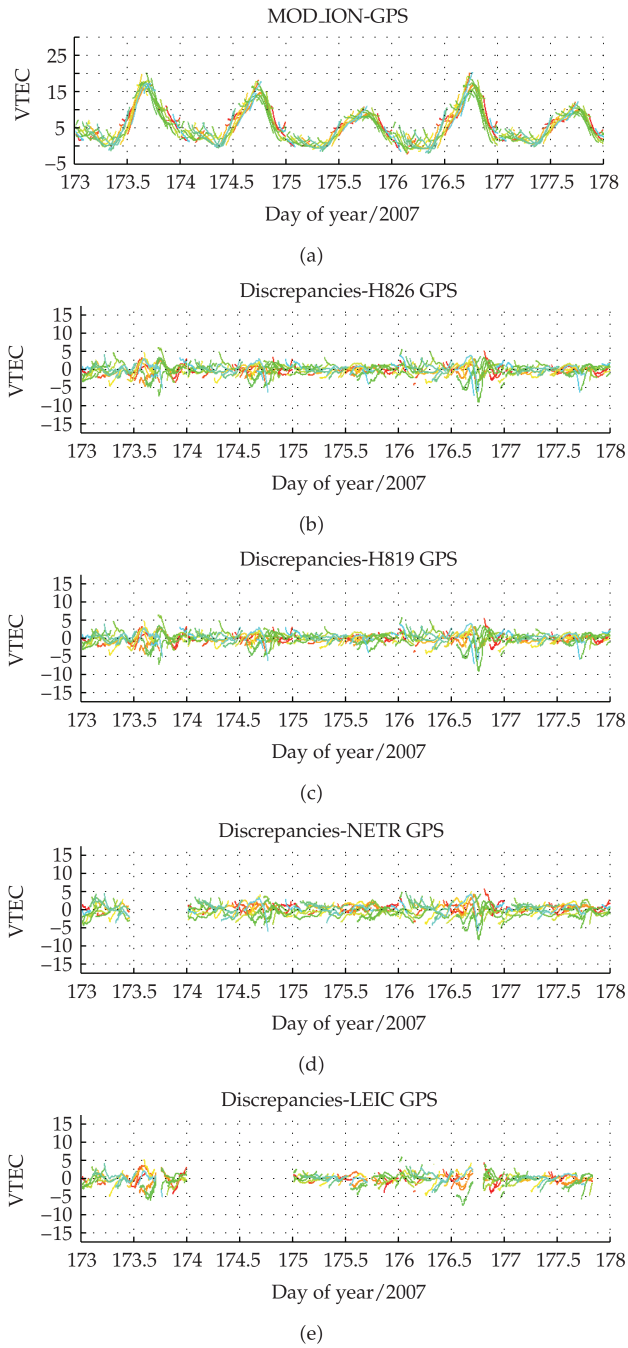

Figure 7: VTEC and discrepancies (GPS: 173 to 177/2007).

5. Conclusions and Future Works

Results showed that, when using only GPS observables, you get the estimation of satellites IFBs with RMS better than 2.735 TECU, and better than 0.329 TECU for those of receivers.

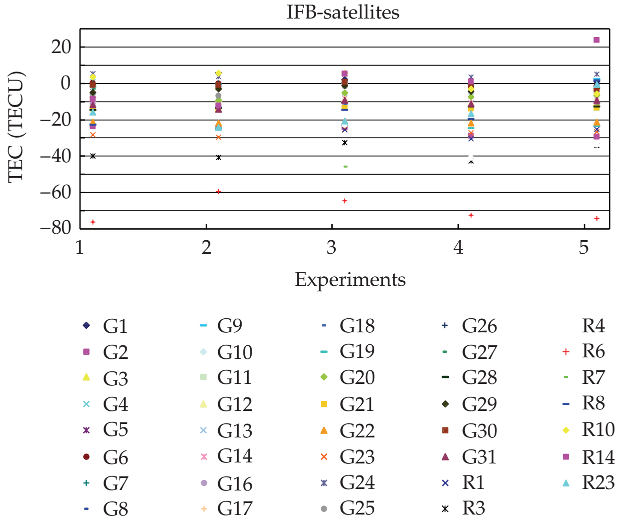

Figure 8: GPS and GLONASS satellite IFB—Error in TEC.

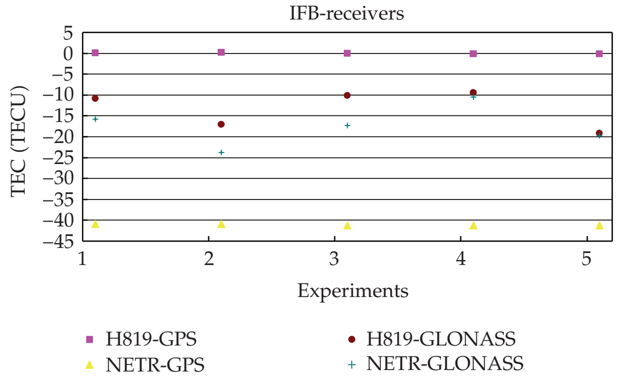

Figure 9: GPS and GLONASS receiver IFB—Error in TEC.

It represents, respectively, in L_1 carrier, errors of 0.444 m and 0.054 m, respectively, for satellites and receivers used. The RMS obtained for the estimation of the VTEC is better than 2.713 units, which for L_1 carrier is an error of 0.441 m. The RMS obtained by integrating GPS and GLONASS was better than, respectively, for the satellites and receivers IFBs and VTEC of 12.727, 4.364 TECU, and 4.929 VTEC units, representing an error of 6.568 m in L_1 carrier, 0.709 m, and 0.800 m respectively. Out of experiments conducted, it is concluded that the GPS observables show better quality than when combined with GLONASS, and compatible with the final values determined with GIM, which is about 2–8 TECU.

Also, new experiments will be conducted using data collected in times of minimum and maximum solar activity, because the solar cycle is the period of minimal activity and periods of irregularities in the ionosphere, having the performance of the model analyzed in the result of absolute and relative positioning with one frequency receivers. In the case of relative positioning, the resolution of ambiguities will also be evaluated.

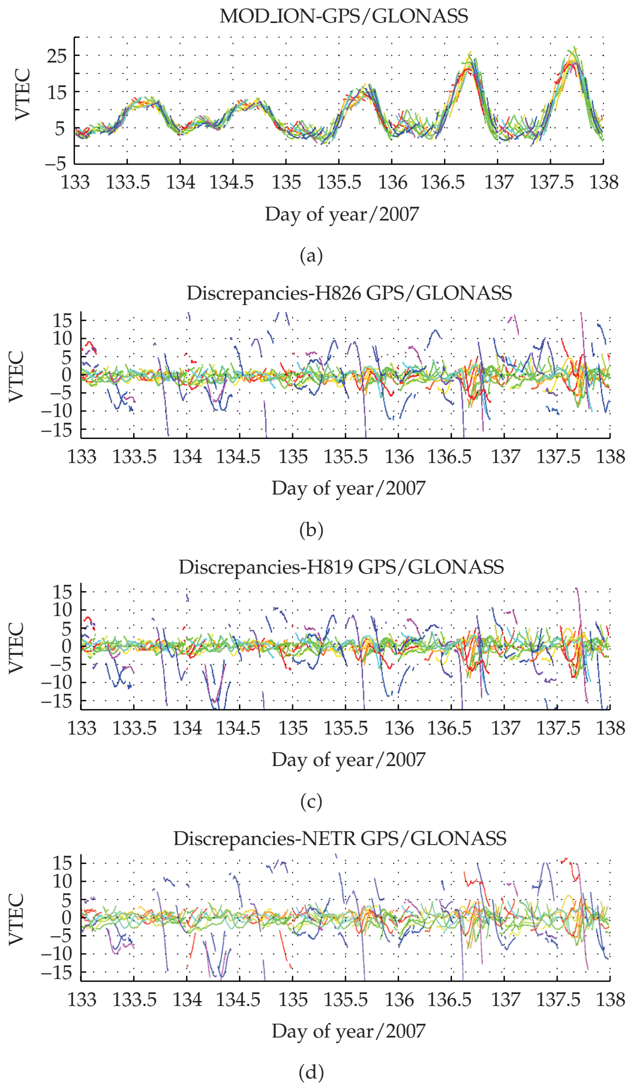

Figure 10: VTEC and discrepancies (GPS/GLONASS: 133 to 137/2007).

About receivers IFBs are necessary to develop methodologies to calibrate and constraint them in the modeling process. It will also be implemented the calculations of effects of 2nd and 3rd orders in the model, in order to provide all the effects of the ionosphere to the users of GPS, GLONASS and, in the future, GALILEO.

And finally, with the modernization and expansion of GNSS networks in Brazil, it is possible to produce maps of the ionosphere in terms of TEC and/or effects on L_1 carrier.

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